A REVIEW OF CATHODE TECHNOLOGIES FOR HPM TUBES

R. B. Miller
SureBeam Corporation

- **Review and Status of Emission Mechanisms**
  - **Thermionic**
  - **Secondary**
  - **Field**
  - **Explosive**

- **Space Charge Limitations**

- **New Approaches**

Contributors and Suggested Readings

Contributors:

Kyle Hendricks, AFRL

Don Shiffler, AFRL

Mike Fazio, LANL

Kim Guenther, HeatWave

Glen Sheitrum, SLAC

Suggested Readings:

- **Gewartkowski and Watson, <u>Principles of Electron Tubes</u>, 1965**
- **Gilmour, <u>Principles of Traveling Wave Tubes</u>, 1994**
- **Cronin, "Modern dispenser cathodes," IEE Proc. 128, 1981**
- **Mesyats and Proskurovsky, <u>Pulsed Electrical Discharge in Vacuum</u>, 1989**
- **Miller, "Mechanism of explosive electron emission for dielectric fiber (velvet) cathodes," JAP, 1998**
- **Litz and Golden, Proc. SPIE, 1994**

Background

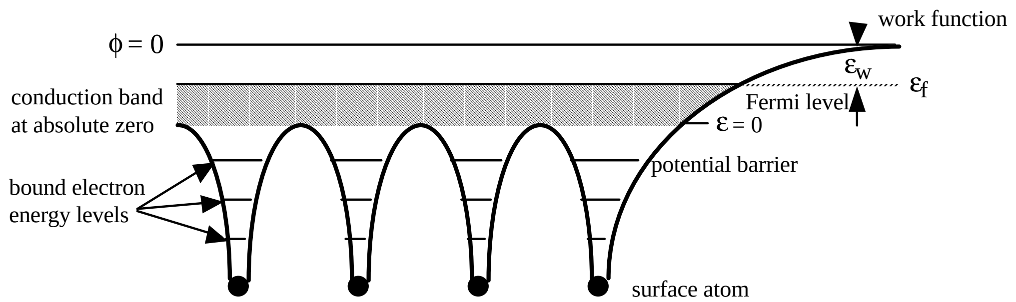
- **All high power microwave tubes rely on a bunched flow of free electrons.**
- **The electron flow is almost always generated by applying a high voltage pulse to a vacuum diode, the cathode of which is capable of emitting a high electron current density, via one of several emission mechanisms.**

Primary Characteristics of an Ideal Cathode (J. R. Pierce, 1946):

1. **Emits electrons freely, without any form of persuasion such as heating or bombardment (electrons would leak off from it into vacuum as easily as they pass from one metal to another;**
2. **Emits copiously, supplying an unlimited current density;**
3. **Lasts forever, its electron emission continuing unimpaired as long as it is needed;**
4. **Emits electrons uniformly, traveling at practically zero velocity.**

What are the most important characteristics for HPM tubes??

Summary of Conditions at the Surface of a Metallic Crystal Lattice



- **Within the lattice, the potential energy diagram is obtained by summing contributions from adjacent nuclei.**
- **Inner shell electrons are bound to individual atoms.**
- **Outer-shell valence electrons are shared by more than one atom in the lattice.**
- **Q-M coupling between outer shell electrons results in the formation of energy bands.**
- **In metals, the lowest energy band (filled valence band) overlaps the conduction band.**
  - **Shared electrons can move freely under the influence of an electric field.**
- **At the edge of the lattice, there is no additional row of nuclei to maintain the low potential energy level.**
  - **The potential difference between a region far outside the surface and the bottom of the conduction band is termed the barrier height, ε_B.**
  - **The potential difference between a region far outside the surface and the top of the conduction band is termed the Fermi level, ε_F.**
  - **The difference between the barrier height and the Fermi level is the work function, ε_W.**

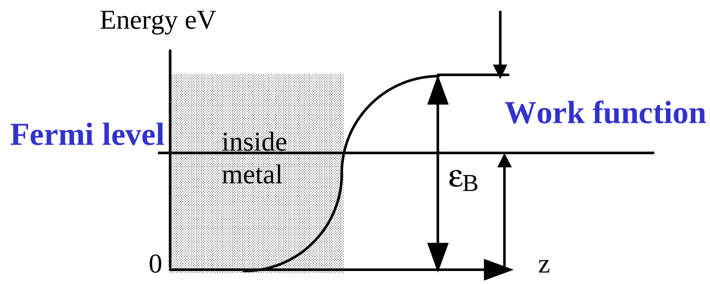
Work Functions for Various Metals

- Assume that the zero energy level represents the bottom of the conduction band.
- Electrons in the conduction band obey Fermi-Dirac statistics
  - $f(\varepsilon) = \{1 + \exp[(\varepsilon - \varepsilon_F)/kT]\}^{-1}$

    $\varepsilon_F = 3.64\mathrm{x}10^{-19}\, n_F^{2/3}$, $n_F = N_V / d^3$
- N_V is the number of valence electrons per atom, and d is the lattice spacing.
- A crude estimate for the barrier height is

    $\varepsilon_B = 0.33\, [e^2 N_V / (\pi\varepsilon_o d)]$
- The work function is the difference between the barrier height and the Fermi level:

  $\varepsilon_W = \varepsilon_B - \varepsilon_F = 8.3 - 6.9 = 1.4$ eV, for Cs
  (N_V = 1, and d = 2.3 Angstroms)



Metal	ε_w (eV)*	Melting Point (oC)
Aluminum	3.7	660
Barium	2.3	725
Carbon	4.4	~3550
Cesium	1.9	28
Copper	4.5	1083
Gold	4.6	1064
Iridium	5.2	2410
Iron	4.4	1535
Molybdenum	4.3	2620
Osmium	5.4	3045
Rhenium	5.1	3180
Thorium	3.4	1750
Tungsten	4.5	3410

Pure metals with low work functions have low melting points.

Emission Mechanisms

- **Supply additional energy to electrons in the conduction band such that $\varepsilon > \varepsilon_W$.**
  - **thermionic emission (apply heat - 1000 ^oC)**
  - **photoemission (apply photons with $h\nu > \varepsilon_W$; 4000 Ang. = 3.1 eV)**
  - **secondary emission (electron bombardment; > 100 eV)**

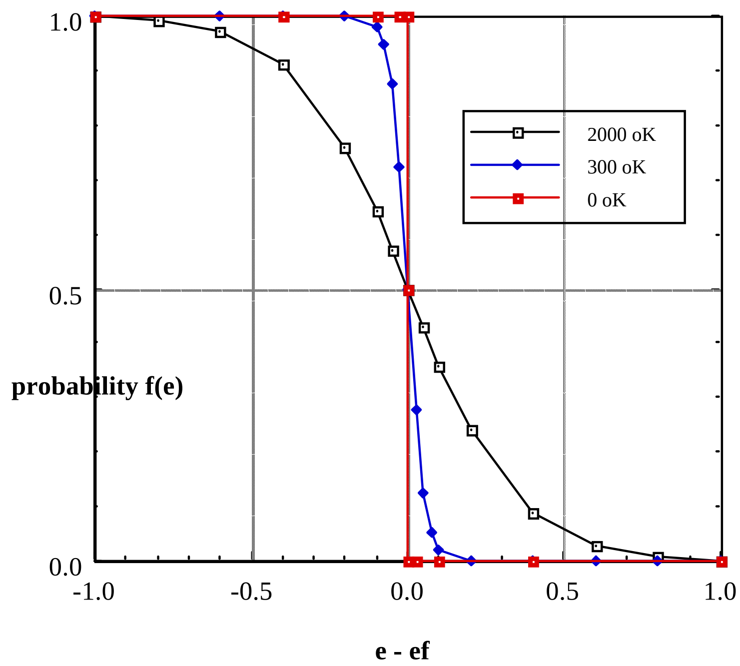
- **Modify the potential barrier.**
  - **field emission (apply a very strong electric field; 10^7 V/cm)**
  - **explosive emission (form a plasma on the surface; $\varepsilon_W = 0$)**

At present, the important emission mechanisms for high-power tubes include

thermionic emission
explosive electron emission

Thermionic Emission

- The kinetic energy of electrons in the conduction band depends on the temperature.
  - $f(\varepsilon) = \{1 + \exp[(\varepsilon - \varepsilon_F)/kT]\}^{-1}$
- The critical z-directed momentum for escape from the surface is
  - $[p_{zc}^2/(2m)] > \varepsilon_B = \varepsilon_F + \varepsilon_W$
- The emission current density is found by integrating the +z directed current of electrons in the conduction band over all momentum states.
- The result is the Richardson-Dushman equation:
  - $j\ (\text{amps/m}^2) = 1.2 \times 10^{-6}\ T^2 \exp(-\varepsilon_W/kT)$



The thermionic emission current density is a function of the temperature and the work function.

Evolution of Thermionic Cathodes

1. **Directly-heated W filaments**

    •geometry limitations; ac "heater hum"

2. **Indirectly-heated cathodes**

    •oxide coatings to reduce the work function (1.6 eV). (These are almost never used in HPM tubes. They tend to blister, are destroyed by ion bombardment, and are easily poisoned.)

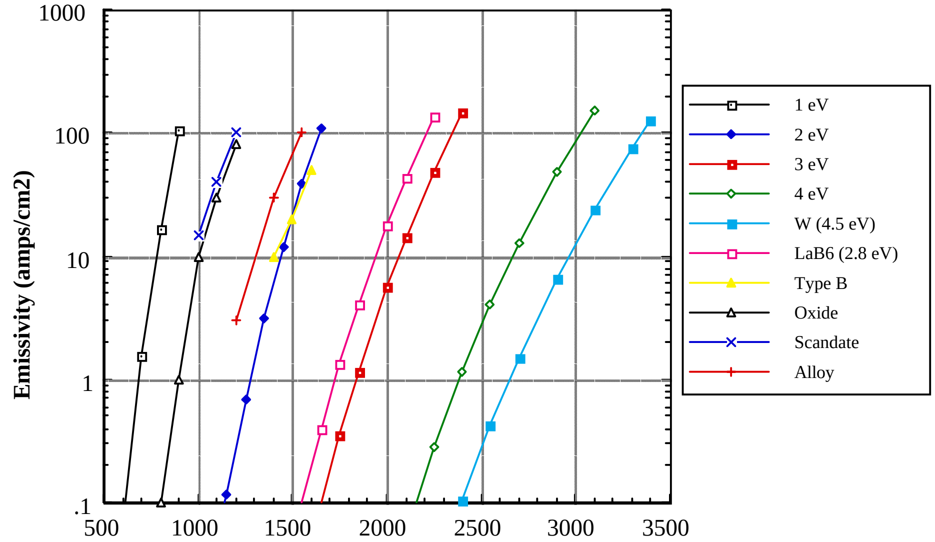
3. **Dispenser cathodes**

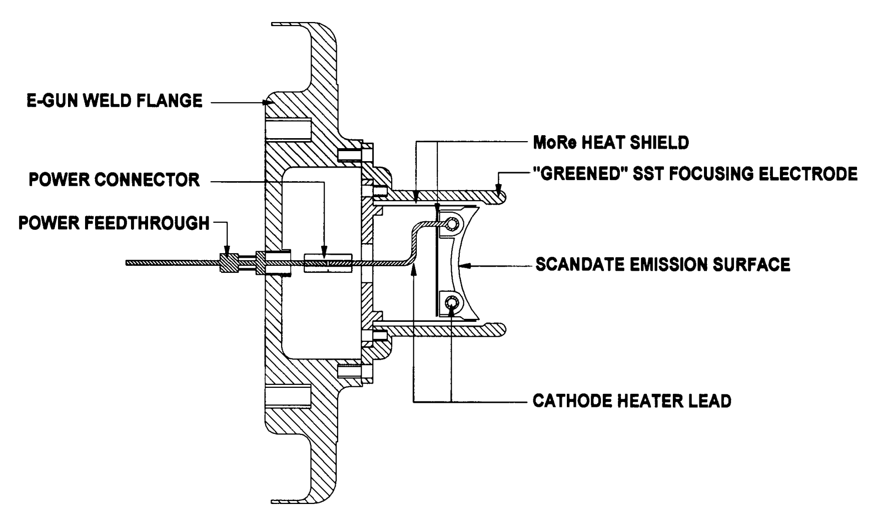
    •porous W matrix impregnated w/ BaO, CaO, Al_2O_3. (B: [5:3:2]; S: [4:1:1])

    •M-type (alloy) is an S or B coated with a thin layer of Ir, Os, or Rh to further reduce the work function. (Film is subject to deterioration.)

    •Scandate cathodes have about 5% by weight of Sc_2O_3 mixed into the W matrix, which is then impregnated. The work function is < 1.5 eV; 10s of A/cm^2 for 1000s of hours.

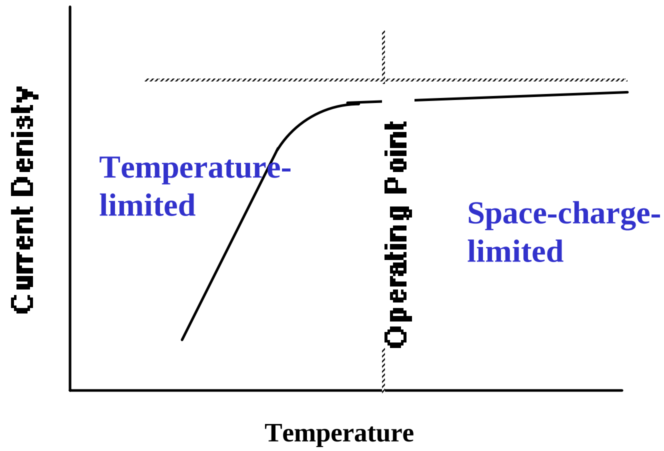
Caution: susceptibility to poisoning varies inversely with temperature.

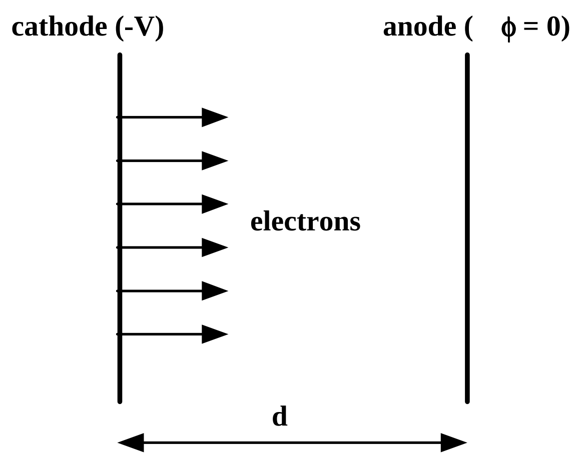




Space-Charge-Limited Flow

- The current density from a thermionic cathode is temperature-limited at low temperatures, and space-charge-limited at high temperatures.
- Thermionic cathodes are usually operated just into the space-charge-limited region.
  - This eliminates the need for precise temperature and work function uniformity over the surface, and eases voltage and current stability requirements for the cathode heater.
- The critical assumptions for estimating the space-charge limit are the following:
  - the electric field *vanishes* at the cathode surface
  - the emitted electrons have *zero* initial velocity
- The one-d planar diode result is given by the Child-Langmuir law:
  - $j = (4/9)\ \varepsilon_o (2e/m)^{1/2}\ (V^{3/2}/d^2)$
  - $= 2.33 \times 10^{-6}\ (V^{3/2}/d^2)\ (\text{amps/m}^2)$

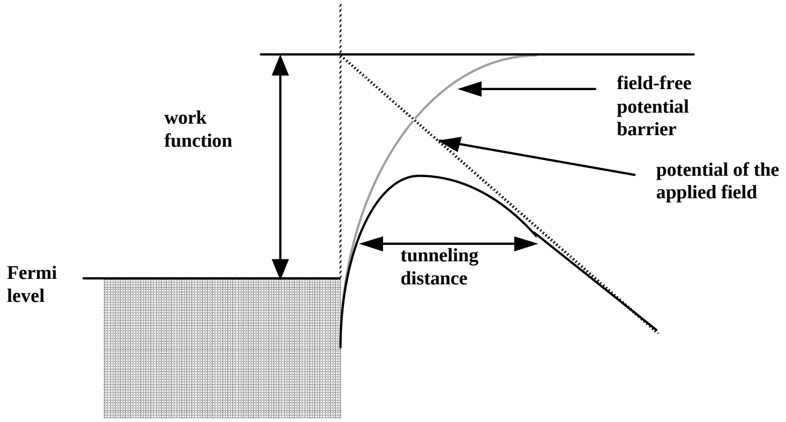




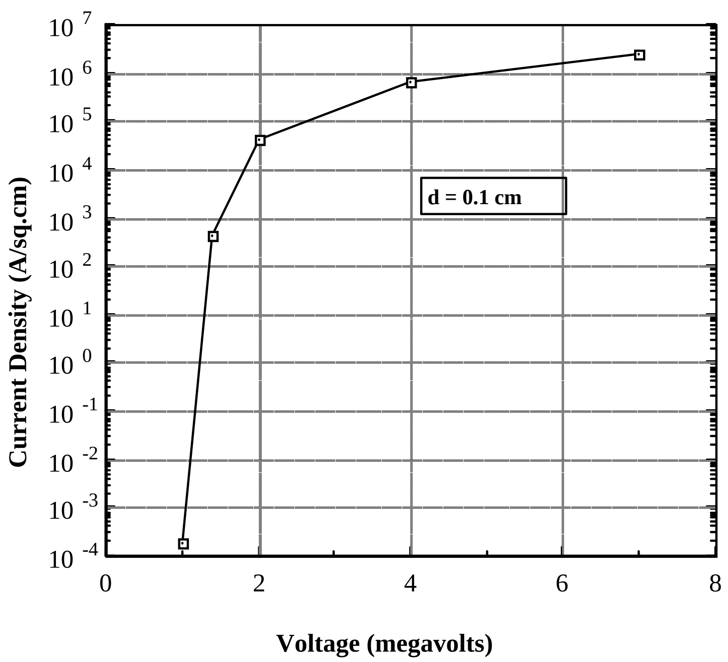
Electron Field Emission

- When the electric field at the surface of a thermionic cathode reaches a critical level, the diode current is observed to rise sharply - the potential barrier is distorted by the applied field.
- Electrons are able to “tunnel” through the barrier. The barrier penetration probability depends on the work function, the Fermi level and the field strength:

$$\psi^*\psi \sim \exp\{[(-2\pi\varepsilon_B)/(heE_a))](2m\varepsilon_W)^{1/2}\}$$

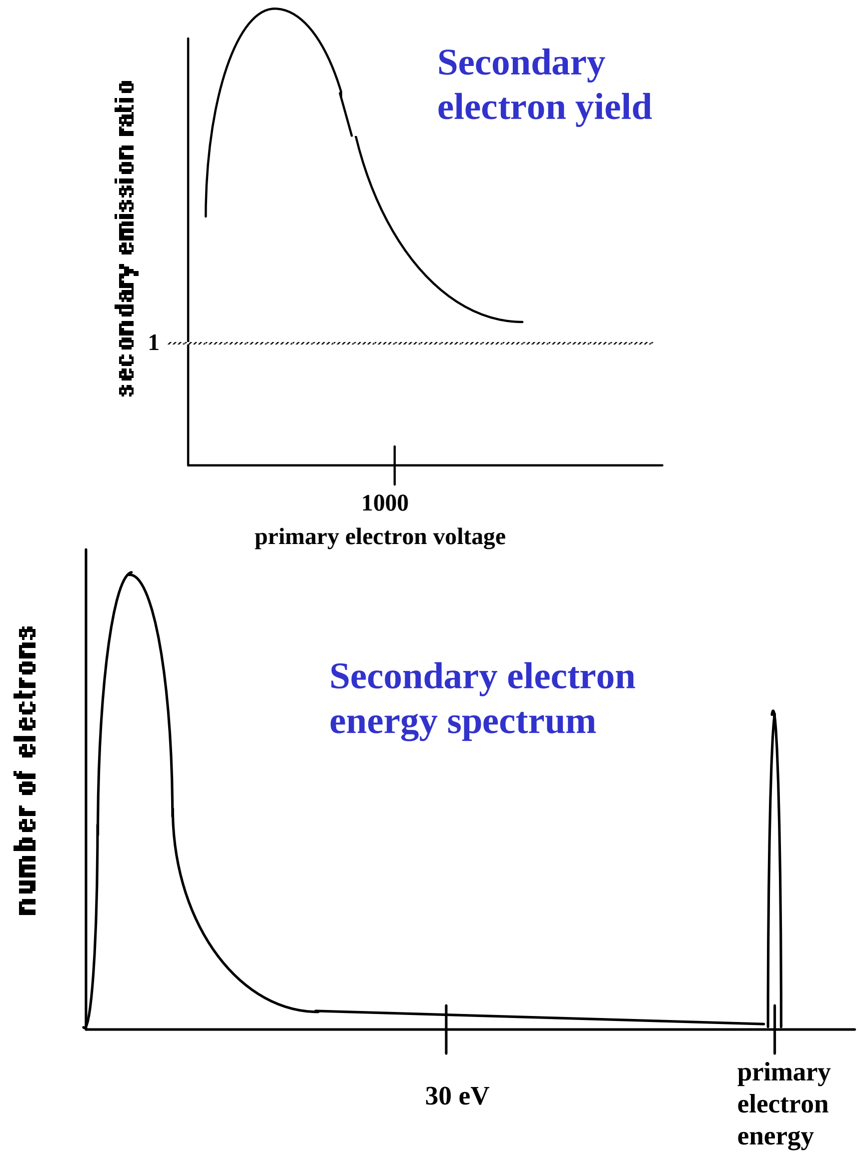


- The required electric fields are quite high (10^7-10^8 V/cm)
- The emission current density is given by the Fowler-Nordheim equation, corrected for space-charge effects. The current density is an extremely sensitive function of the field.
- To date, field emission cathodes have been fabricated in arrays (FEAs), with the tip design providing significant field enhancement.
  - Ion back bombardment can cause a serious deterioration of performance
  - Transition to explosive emission must be avoided



Secondary Electron Emission

- Secondary emission current is proportional to the incident primary electron current.
- Secondary emission ratios of > 10 can be achieved, but the actual value depends strongly on the surface preparation.
- Secondary emission is often used in conventional crossed-field tubes to decrease (or eliminate) the required heater power.
- A novel application of the "multipactor" instability with optimized secondary emission has resulted in a electron gun which directly generates a modulated beam.
  - See Mako and Peter, IEEE PAC 1993



Explosive Electron Emission

EEE: The emission of electrons from a plasma created on the cathode surface by the application of a strong electric field.

- Field-enhancement EEE (**See Mesyats**)
  - usually metallic surfaces
  - field-enhancement at the tips of microprotrusions causes explosive vaporization
  - fields at the tip are generally $> 10^7$ V/cm (enhancement factors in the range of 10-1000)
  - minimum plasma temperature is few thousand degrees K.
  - closure velocities generally exceed 1 cm/μsec, and can quickly short the diode.

- Surface-flashover EEE
  - usually dielectric/metal interfaces (velvet on Al)
  - plasma generated by a surface flashover mechanism at 10s of kV/cm.
  - plasma can be quite cold, with closure velocities as low as 0.2cm/μsec.
  - a significant amount of cathode material is liberated in the process. This can limit the pulse duration and/or the pulse repetition rate.

Velvet Cathode Baseline

Velvet Description:

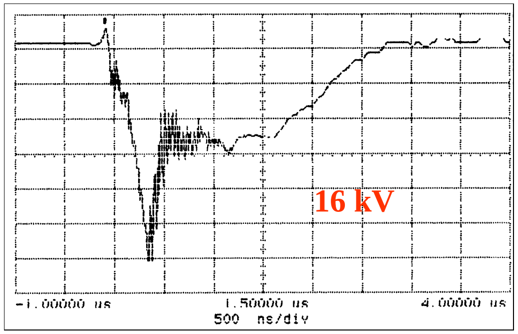
Arrays of tufts, with each tuft consisting of forty 10-20 micron diameter fibers, one millimeter in height. The fibers are 75% rayon, 25% silk.

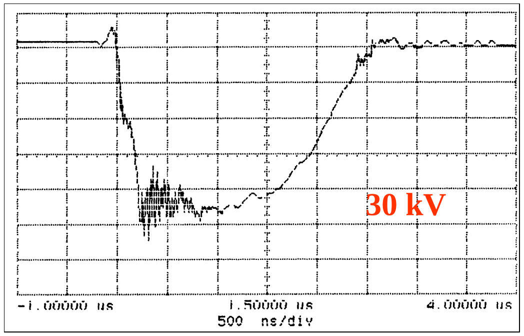
Velvet Type	Tuft Density (per centimeter)
red	14 x 14
maroon	12 x 12
green	16 x 16
double row green	5 x 16

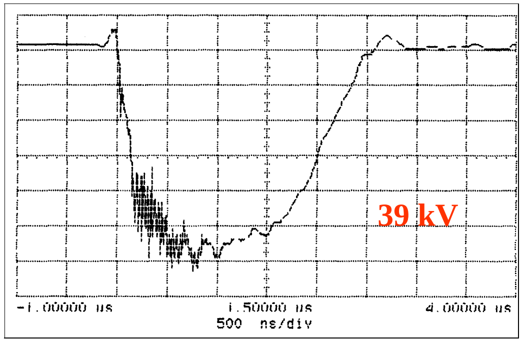
Single-Pulse Velvet Results:

1. **Velvet abruptly turns-on at low E-field stress (<25 kV/cm). The diode voltage at which turn-on occurs decreases with increasing dV/dt.**
2. **The diode impedance remains nearly constant for 1.5 microseconds, suggesting a closure velocity < 0.25 cm/µs.**
3. **Beam current during flat-top agrees well with EGUN simulations.**
4. **Single pulse waveforms are nearly identical for all velvets. (Some impedance collapse for double row green late in the pulse.)**

25 kV/div

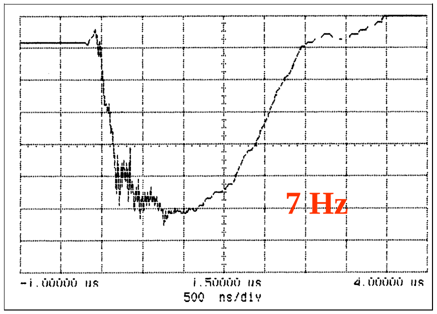


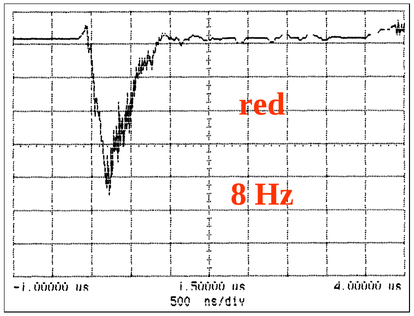


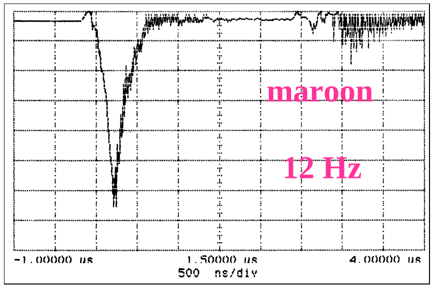


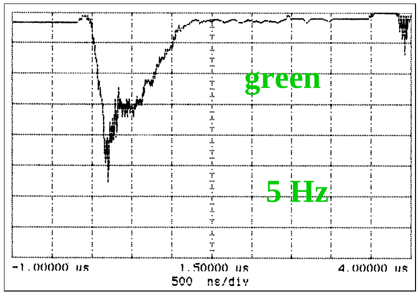
Velvet Cathode Baseline (2) Repetitive Pulse Results

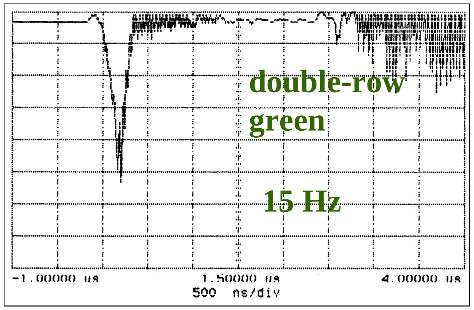
25 kV/div







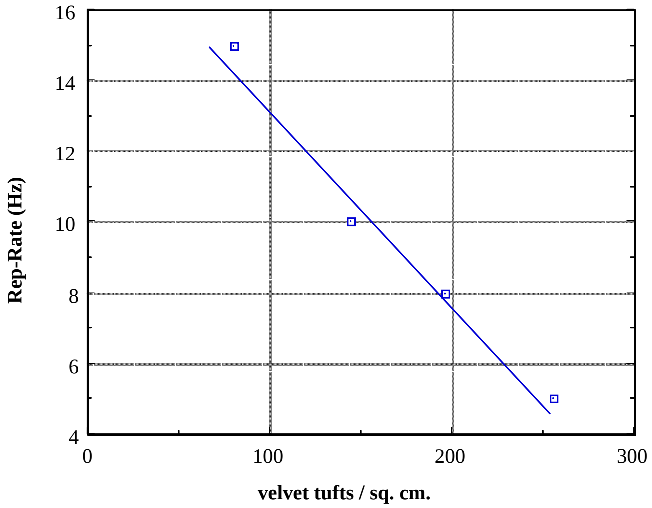




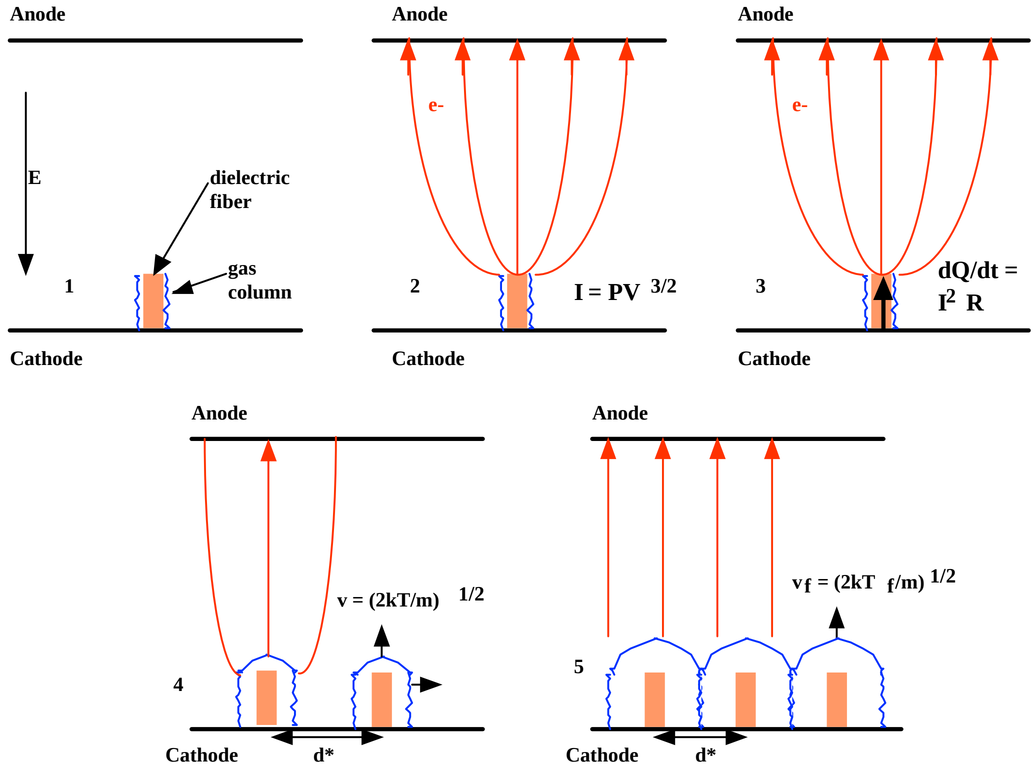
S_{eff} = 150 liters/sec; A_c = 28 cm^2.
For 1.75 microsecond pulses, expect difficulty at 10 Hz (red velvet).

- 100 pulse burst at 7 Hz OK; pressure rise to 9x10^{-5} torr
- Pressure exceeds 1.5 x 10^{-4} torr for 50 pulses at 8 Hz

Achievable PRF depends on tuft density.



Proposed Model of Explosive Electron Emission for Dielectric Fiber Cathodes



Five steps involved in the explosive emission process for dielectric fibers:

(1) Surface flashover generates a cold, dense plasma/gas column.

(2) The applied electric field extracts a space-charge-limited current flow.

(3) The flow of current resistively heats the gas column.

(4) The gas columns expand at a rate determined by the gas temperature.

(5) The gas continues to expand into the anode-cathode gap.

Quantitative Estimates for Velvet (Titan)

Estimated Final Temperatures and Closure Velocities for Titan Velvet Cathode Experiments

VELVET	75 kV		150 kV	
	T_f (^oK)	v_f (cm/μs)	T_f (^oK)	v_f (cm/μs)
red	359	0.17	565	0.22
maroon	398	0.18	709	0.24
green	339	0.17	496	0.20
double-row green	542	0.21	1020	0.41

For typical Reltron gun parameters, diode closure rates of velvet cathodes are relatively low. However, modest increases in perveance and/or voltage can produce significant increases in the temperature and closure velocity of the cathode plasma.

Useful rule-of-thumb is v_f (m/s) = $100\ (d^*/d)^{2/3}\ V^{1/2}$

Example: red velvet with

V_d = 500 kV, d = 1 cm

T_f = 8750 ^{o}K
v_f = 1.2 cm/μs

Implications for long-pulse diodes with velvet cathodes:

Uniform emission from a dense array of micro-emitters

Keep field stress low if possible

Avoid field enhancement

Pulse Repetition Rate is Pressure-Limited

If the base pressure is sufficiently low,

$$P\ (\text{torr}) = \frac{Np(\text{atoms/pulse})\ R(\text{pulses/sec})}{[3.5E19\ \text{atoms/liter/torr}]\ S_{eff}(\text{liters/sec})}$$

N_p is the number of atoms liberated from the cathode in one pulse
R is the pulse repetition rate
S_{eff} is the pumping speed of the vacuum system

CEG L-band: P = 10^{-4} torr, S_{eff} = 180 liters/sec, R = 1 Hz

Np = 6.2E17 atoms/pulse

CEG S-band: P = 10^{-4} torr, S_{eff} = 15 liters/sec, R = 1 Hz

Np = 1.0E17 atoms/pulse

Dividing by the cathode area gives

3.5E15 molecules/cm^2/pulse

The severe cathode damage observed after tube operation in the > 10^{-4} torr pressure range suggests ion back-bombardment. After Olson, the ion density growth can be modeled as an avalanche process:

$$dn_i/dt = n_b/\tau_e + n_i/\tau_i$$

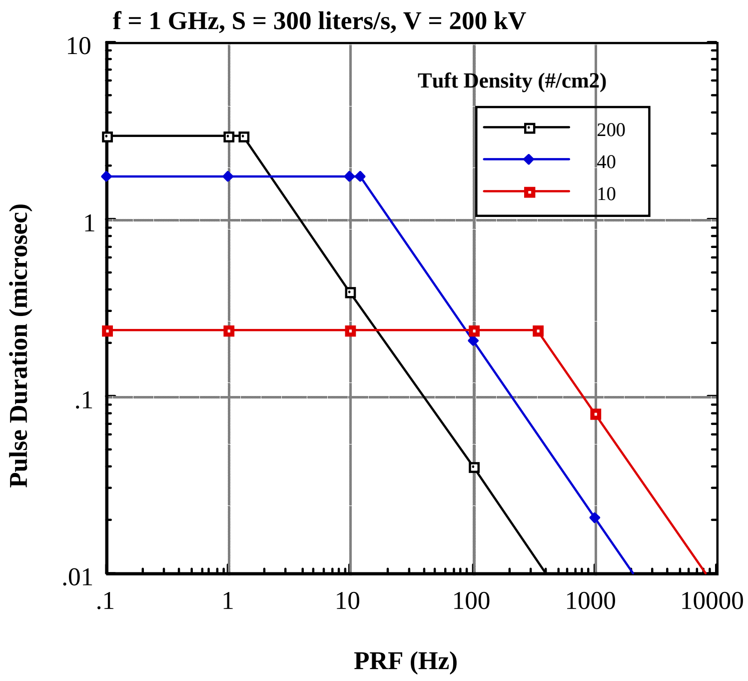
τ_e and τ_i are the phenomenological electron impact ionization and effective ion avalanche times. For hydrogen

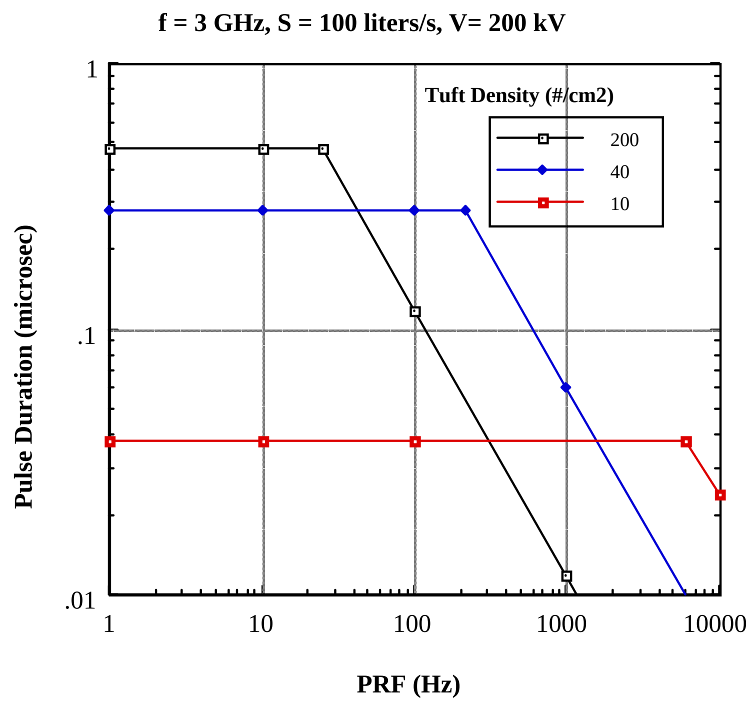
$\tau_e = 5 / [P(\text{torr})]$, $\tau_i = 0.33 / [P(\text{torr})]$

If the voltage pulse duration is comparable to the ion avalanch time, we expect ion back-bombardment:

Velvet Repetition Rate Criterion:
$R(\text{Hz}) < 3300\ S_{eff}(\text{liters/s}) / [A_c(\text{cm}^2)\ \tau\ (\text{ns})]$

Cloth Fiber Cathode Performance Limitations

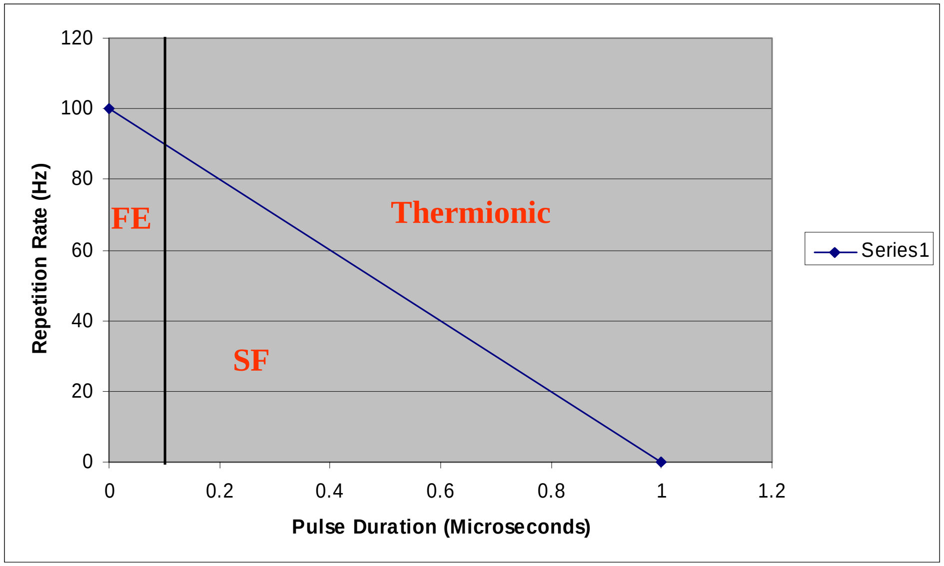




- one microsecond, 50 Hz may be achievable at 1 GHz
- 500 ns is a reasonable upper limit for 3 GHz

HPM Cathode Summary

- **The important emission mechanisms for high-power tubes include thermionic emission and explosive electron emission.**
  - **secondary emission may be applicable in cross-field tubes**
  - **true, stable field emission is difficult to realize**
- **Choice of cathode depends on application.**
- **Desirable features for HPM tubes:**
  - **free electron emission at the space charge limit**
  - **emission of no extraneous material**
  - **lasts forever**
  - **vacuum condition tolerant**



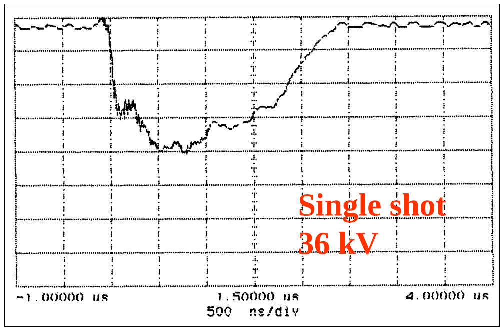
Characteristic	Thermionic	EEE - FE	EEE - SF
SCL emission	T ~ 1000 oC	E > 100 kV/cm	E > 20 kV/cm
No extra material	Ba evaporation	> 10^{14} mol/cm^2	> 10^{15} mol/cm^2
Lifetime	1000 hrs @ 10 A/cm^2	10^6 shots	10^5 shots
Vacuum conditions	< 10^{-7} torr	10^{-6} - 10^{-4} torr	10^{-6} - 10^{-4} torr

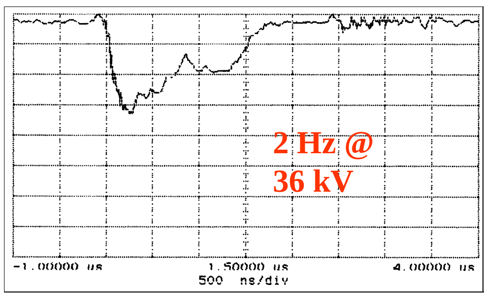
A Few New Topics

- Improved lifetime of dispenser cathodes at high emission density. (Scheitrum - SLAC)
  - In-situ deposition of oxide layers. Eliminate impurities, improve uniformity. Goal is to maintain a low, uniform work function over the emitting surface. Operate at lower temperatures, reduce the barium evaporation rate. (lifetime of 1000 hours at 100 amp/cm^2)
- Explosive emission materials with low closure rates and reduced gas output.
  - AFRL using CsI-coated carbon fiber. (With a good vacuum system, velvet quits emitting!)
  - Glass or ceramic fibers (Smith - Titan/PSI)
- Ferroelectric cathodes. (Nation - Cornell)
- Combine micro-pulse gun (Mako), or photoemission (Lasertron), with enhanced secondary emission, + post-acceleration. Start with well-bunched beam, avalanche the current, post-accelerate to supply additional energy -- high power with very high efficiency?

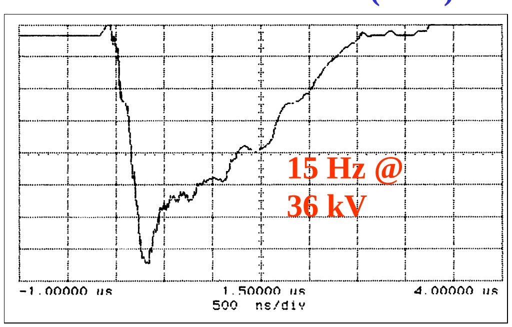
Performance of Other Cathode Materials

Titan carbon fiber

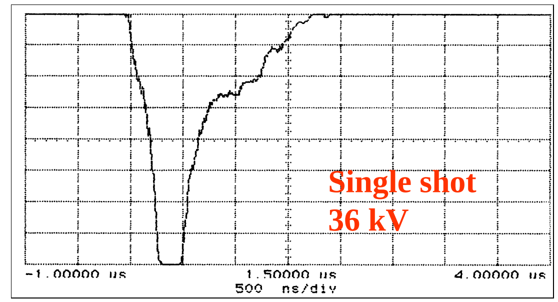




CsI-coated carbon fiber (Voss)



ORNL graphite foam



Russian metal/ceramic